Chapter 1. HISTORICAL PERSPECTIVES

Arnauld E. Nicogossian
Roger D. Launius
Deborah F. Pober
Stephanie A. Roy

Flight has long been a dream of humanity. Less than a century after the Wright Brothers first realized their dream in 1903, we are about to realize an equally significant accomplishment: the permanent habitation of space on board the International Space Station (ISS).

Fifteen nations are working together to construct, operate, and utilize the ISS, an orbiting space laboratory with capabilities that surpass space research platforms past and present. Supporting a crew of seven, the ISS will accommodate a broad range of biomedical, physical science, technology, Earth science, and space science experiments.

The International Space Station represents the next step in the long-range plans of many of the world's space agencies: permanent human habitation in space and long-duration exploratory missions into the solar system and beyond. Before these goals can be fully achieved, a number of biomedical and technological challenges must first be overcome. While biomedical scientists have been working on a number of these questions since the inception of the space program, others have come to light recently or may not arise until the ISS is occupied. In order to put these challenges into historical perspective, this chapter begins with an overview of the challenges and visions of spaceflight and space medicine pioneers.

THE ORIGINS OF ROCKETRY

The roots of spaceflight can be traced back to the beginning of rocketry over 2000 years ago with the invention of gunpowder in China. By the time of Ghengis Khan's reign, gunpowder in the form of firecrackers and crude rockets had become an integral part of Chinese village defense.

Eventually, travelers and explorers introduced gunpowder and rocketry to Europe, and visions of space travel soon followed. In the mid-1600s, French author Cyrano de Bergerac not only wrote about space travel, but also suggested several methods of achieving it. His works *Histoire comique des etats et empires de La Lune* and *Histoire comique des etats et empires du Soleil* sketched different approaches to interplanetary travel. Some were slightly farfetched—one idea involved tying bottles filled with dew to a traveler and then waiting for the dew's evaporation to carry the traveler upwards—but others approximated 20th century reality. One of de Bergerac's travelers reached the Moon via rocket thrust; De Bergerac also described the use of parachutes for return from space travel.

In the 19^{th} century, the progress and modernization of the Industrial Revolution, as well as Schiaparelli's and Perceival Lowell's announcements of "canals" on Mars, catalyzed a spate of new space exploration fiction. Jules Verne's 1865 novel *From the Earth to the Moon* sent travelers to the Moon on board a rocket launched from the Florida coast. Thirty years later, H.G. Wells' *The War of the Worlds* brought invading Martians to Earth and featured a perspective on space exploration: the clash of ecosystems.

Rockets with modern military uses emerged in the 19^{th} century. William Cosgrove's rockets were used in both the English war with France and the War of 1812. These rockets were three-feet long and liquid fueled, and could launch a 24-pound missile from land or sea with one-mile accuracy. Although more accurate weapons temporarily replaced rockets in military arsenals, the whaling and shipping industries adapted the rocket for other uses, including the rocket-launched harpoon.

At the beginning of the 20^{th} century, three men working along parallel paths laid the groundwork for modern rocketry: Konstantin Tsiolkovsky in Russia, Hermann Oberth in Germany, and Robert Goddard in the United States. In 1903, Tsiolkovsky, the "Father of Cosmonautics," presented in mathematical terms the velocity a rocket would need to escape Earth's gravity. In later papers, Tsiolkovsky described the use of rockets for launching orbital satellites and interplanetary ships, detailed specific flight methods, suggested liquid oxygen and liquid hydrogen as rocket fuel, proposed the multistage rocket, and even discussed the requirements for sustaining life on board a space station. Tsiolkovsky was solely a theorist , however, and never tested his hypotheses.

At the same time, scientist and professor Hermann Oberth was investigating the use of rockets for propulsion in Germany. In 1923, Oberth's paper, *Die Rakete zu den Planetenarumen* (*Rockets in Planetary Space*), addressed almost all aspects of rocket travel, including escape velocity, multiple stages, and fuel mixtures. Shortly before World War II, Oberth joined his former pupil Werhner von Braun in Germany's secret facility at Peenemünde, where they both worked on the development of the V-2 rocket.

In the United States, Robert Goddard was also exploring the principles of rocketry. As a graduate student in physics, Goddard received two patents: one for using a mixture of solid and liquid rocket fuel and another for the multistage rocket. In 1917, Goddard received a $5000 grant from the Smithsonian Institution to continue his research. The resulting 1919 publication, *Method of Reaching Extreme Altitudes*, demonstrated how rockets, whose estimated path was based in part on his correct calculations of escape velocity, could be used to explore the upper atmosphere.

The era of modern rocketry truly began with Goddard's rocket launch on March 16, 1926. This launch flew to an altitude of 184 feet and remained aloft for only 2.5 seconds—shorter than the Wright Brothers' first flight—but it was the first successful flight of a liquid-fueled rocket. Later, Goddard launched the first instrumented payload (a barometer, a thermometer, and a camera to record the readings) in 1929, although it only reached an altitude of 90 feet before crashing back to the Earth's surface.

Goddard eventually moved to an area near Roswell, New Mexico, and set up an isolated, independent laboratory. Although his work was not widely recognized until after his death, Goddard developed many of the principles of rocketry and space flight: escape velocity; rockets as a means of providing thrust in a vacuum; liquid propellants; multistage rockets and the associated technology; and even rocket-borne mail delivery, passenger space travel, and interplanetary journeys.

Goddard's New Mexico proving grounds eventually became home to another group of rocket pioneers: the German scientists from Peenemünde who had designed the V-2 under the direction of Werhner von Braun. Although originally designed as weaponry and not as an instrument of propulsion or exploration, the V-2 is considered to be the ancestor of all modern space rockets. First launched in 1942, the liquid-fueled V-2 was meant to be Germany's instrument of victory in World War II. While the it was indeed a model of power and efficiency, Germany was defeated in 1945, a loss that facilitated the transfer of rocket technology and expertise to the United States.

At the end of World War II, "Operation Paperclip" brought both the V-2 program scientists and more than 50 of the actual V-2 rockets to the United States. Wernher von Braun and his associates were offered positions with the U.S. Army designing rocketry and, later, long-range nuclear weapons. With the beginning of the space race in the late 1950s, von Braun's team turned to the systems that would eventually carry America into orbit and to the Moon.

After Tsiolkovsky, Oberth, and Goddard advanced rocket capabilities, the development of space flight was rapid. In the 100 years since the Wright Brothers made their first flight at Kitty Hawk, humans have stayed in space for months at a time, guided robotic craft to seven other planets, and are now transitioning into a permanent human presence in space.

The need to sustain life and productive human function during space flight has presented many unique challenges in the areas of medicine and life-support technology. Concurrent advances in spacecraft design and mission sophistication have spurred numerous technological breakthroughs in the biomedical sciences, including the development of medicine for remote and hostile environments. The symbiotic relationship between astronautics and medical science will continue to further space exploration and benefit terrestrial medicine.

THE ORIGINS OF SPACE MEDICINE

, Although human space flight and the related need for the specialty of space medicine were not accorded serious consideration until the development of the V-2 rocket, the foundation of space medicine can be traced to early programs in occupational and aviation medicine. H.G.

Armstrong foresaw this need and, in 1948, organized a meeting at the USAF School of Aviation Medicine to discuss aeromedical problems of space travel (von Beckh, 1979). Presentations were made by then-Colonel Armstrong, Professor Hubertus Strughold (later regarded as the "father of space medicine"), and astrophysicist Dr. Heinz Haber. This meeting marked the beginning of a new discipline within the field of preventive medicine: aerospace medicine soon emerged as a growing specialty.

Interest in the possibility of human space flight grew rapidly among biomedical scientists. This interest was fueled in part by concern over the health and safety of pilots involved in supersonic research flights. Conditions faced by crews aboard these flights were similar to those later encountered in orbital space flight. To learn more about how the body adapts to space flight, the United States launched two primates into space on board V-2 rockets by 1950. Although neither animal survived, these early flights demonstrated the need for reliable life-support systems and began the long process of requirements definition for the protection of mammals against the rigors and stresses of space flight.

Scientists soon recognized the need for an organization to coordinate and exchange information concerning space medicine research. In 1950, a distinguished committee comprised of Drs. A.C. Ivy, J.P. Marbarger, R.J. Benford, P.A. Campbell, and A. Graybiel petitioned the Aeromedical Association to admit a space medicine branch. In 1951, the petition was accepted and space medicine was accorded formal recognition within the broader medical community.

Many early practitioners of space medicine were trained in the aviation medicine programs of the Navy and the Air Force. Beginning in the 1950s, these two organizations expanded their curricula to include topics of interest to space medicine. These new directions were reflected by new organizational designations: the Air Force facility became the School of Aerospace Medicine and the Navy school became the Naval Aerospace Medical Institute. The schools of public health at Johns Hopkins, Harvard, and Ohio State Universities, which cooperated with the military facilities in providing residency training, also reflected the changing focus in their curricula.

Space medicine gained more public notoriety in November 1951 when the managing editor of *Collier's* magazine, one of the most popular weekly periodicals of the era, dispatched associate editor Cornelius Ryan to cover a space medicine symposium in Albuquerque, New Mexico. There, Ryan learned of the concerted efforts to anticipate and prepare for the rigors of human space flight. Although Ryan was skeptical that humans might explore space, he was treated to dinner by several of the participants and soon was convinced otherwise. Wernher von Braun, representing the Army Ballistic Missile Agency at Huntsville, Alabama, took the lead in proving that human space flight was not only possible, but that it was the humanity's destiny as a species. Harvard University astronomer, Fred Whipple, recalled the event: "Whether or not he was truly skeptical, we persevered. Von Braun, not only a prophetic engineer and top-notch administrator, was also certainly one of the best salesmen of the 20th century….and finally by midnight he [Ryan] was sold on the space program" (Ordway and Leiberman, 1992).

Interest in the possibility of orbital space flight continued to grow in both the United States and the Soviet Union throughout the 1950s. On October 4, 1957, Sputnik 1 was launched successfully into Earth orbit. Public interest in U.S. space efforts surged after the flight of this Soviet satellite, and the two nations became engaged in a "space race" that allowed little time for leisurely planning and development. The sense of urgency that permeated American space planning after 1957 had considerable implications for space medicine.

Skeptical members of the biomedical community, however, still questioned the ability of humans to perform successfully in space, let alone to withstand the combined stresses of launch and reentry. In 1958, the National Academy of Sciences National Research Council Committee on Bioastronautics identified several potential problems for astronauts (Table 1-1). Some of the Committee"s predictions were eventuallyborne out while others were not.

The hectic pace of space activities during the late 1950s left little time for systematic space biomedical research. Issues of life support, safety, and health had to be addressed *a priori*, building principally on the tenets of aviation and occupational medicine. (The first space suits, for example, were a direct outgrowth of the Navy full-pressure suit used for high-altitude flights.) As a result, new knowledge was generated more from mission results than from research conducted in laboratories and ground-based simulations.

The remainder of this chapter considers the human space programs conducted by the United States and the former Soviet Union and reviews key biomedical problems and findings. These histories weave a tale of maturing space medical capabilities, first spurred by national necessity and competition, and then increasingly driven by systematic research priorities. This chapter also examines the programs of other participants in human spaceflight: the members of the European Space Agency, Canada, and Japan. Tables 1-13 and 1-14 at the end of this chapter summarize the human space missions and extravehicular activities, respectively, completed to date.

THE AMERICAN HUMAN SPACE PROGRAM

Project Mercury

The National Aeronautics and Space Administration (NASA), formed in 1958, was charged by the President of the United States to launch a person into space in a manner that allowed effective performance and safe recovery of the crewmember. That charge was given high national priority, second only to national defense, and was soon realized in Project Mercury. At the same time, NASA worked with the support of leading life scientists to develop a capability for extended human space missions (Lovelace, 1965).

Even before the first astronaut candidates were selected, medical scientists and practitioners faced many unknowns as they prepared for the first Mercury launch. The selection process began with the direction from President Eisenhower that all astronaut candidates be recruited from the ranks of military test pilots. As a group, military test pilots were required to demonstrate many abilities crucial to being an astronaut: good judgment made in threatening situations, quick decision making, and refined motor skills. Of the first group of applicants, 100 test pilots were given interviews, psychiatric examinations, and a complete medical evaluation that included medical stress tests (Link, 1965; see Chapter 21). The purpose of these extensive evaluations was to discover any hidden medical problems, to establish baseline levels of physical fitness, and perhaps most importantly, to compile a medical database for each individual against which any changes brought about by later space missions might be measured and quantified. Selection criteria were taken almost directly from those used in military aviation, yet the challenge remained for physicians and others to identify those specific medical parameters that would be most useful in assessing and predicting the ability of humans to adapt to space flight.

Project Mercury required a life support system that would operate without failure under the still relatively unknown conditions of orbital space flight. Fortunately, the fundamental technology for such a system did exist. In 1957, Air Force flight surgeon David R. Simons conducted a 32-hour balloon flight that attained a record altitude of 30,942 meters, buttranslating the technology of his balloon flight into a space system was nonetheless a difficult undertaking. The human requirements for protection, respiratory environment, atmospheric pressure, provision of food and water, and thermal control had to be considered in respect to severe constraints on failure tolerance, size, weight, power, and operation under conditions of thermal extremes, acceleration, and weightlessness. These challenges were met in the end, and the resulting system functioned flawlessly.

Project Mercury was wholly successful in proving that humans could survive and function in the space environment. From beginning to end, the program spanned just two years—May 1961 to May 1963—yet it was able to accomplish very important goals. The primary goal of Mercury to launch and recover a person was reached with Alan Shepard's flight in May 1961 (Figure 1-1), andin all, two suborbital and four orbital Mercury missions were flown, including one that lasted for 34 hours and accomplished 22 orbits of the Earth. All six Mercury astronauts returned to Earth in satisfactory condition.

These missions were valuable for both dispelling and verifying numerous medical concerns. The principal findings of human adaptation to space flight were weight loss, resulting primarily from dehydration, and some impairment of cardiovascular function. Cardiovascular data from the final and longest Mercury flight showed postflight orthostatic intolerance and dizziness on standing, as well as hemoconcentration (Dietlein, 1977). From a behavioral perspective, though, astronauts performed well under conditions of weightlessness. In sum,the program had succeeded in accomplishing its purposes: to successfully orbit a human in space, to explore aspects of tracking and control, and to learn about microgravity and other biomedical issues associated with space flight.

Gemini Program

Planning for the Gemini Program began in May 1961, just after the successful completion of the first suborbital Mercury mission. The two-man Gemini capsule was based upon the experience of Project Mercury and was designed to develop new capabilities, such as extravehicular activities, while providing NASA experience in conducting extended space missions. The program also allowed the biomedical community to delineate the physiological limits of astronaut endurance, an essential step for planning future missions of greater complexity. More specifically, Gemini Program objectives involved the development and testing of procedures and technology needed to:

1. demonstrate the feasibility of space flight lasting long enough to complete a lunar landing;
2. perfect the techniques and procedures for orbital rendezvous and docking of two spacecraft;
3. achieve precisely controlled reentry and landing capability;
4. establish capability for extravehicular activity; and
5. enhance the flight and ground crew proficiency (Mueller, 1967; Hacker and Grimwood, 1977).

Gemini successfully completed 10 human space flight missions, encompassing many notable accomplishments. The program itself was a resounding success as a technological learning program—52 different experiments were performed during its 10 missions. The Gemini accomplishments were a litany of precedents and records: the first U.S. extravehicular activity during Gemini-4 (Figure 1-2), the first rendezvous and docking maneuver during Gemini-8, and the longest mission to date, the 14-day Gemini-7 mission.

During the Gemini Program, biomedical researchers were able to evaluate more fully the changes in cardiovascular function noted during the Mercury program. Cardiovascular changes seen in Gemini crewmembers were regarded as an adaptive response to the intravascular fluid loss resulting from exposure to weightlessness. The question remained, however, whether the observed cardiovascular deconditioning was a self-limiting adjustment.

The Gemini missions reinforced the medical conclusion that humans could live and work in space and could certainly do so for the duration required for the forthcoming Apollo missions. A number of new adaptations to the space flight environment, such as bone mineral loss, were noted (Table 1-2), but none were considered of real consequence for missions lasting two weeks or less. While bringing new issues and concerns to light, Gemini left other medical questions unresolved. The program's biomedical findings nonetheless served to structure and guide experiments to be designed for later, longer missions. Such experiments would be needed to determine the basis and time course of the observed physiological changes.

The bank of data acquired from Gemini bridged the gap between the Mercury program and the next stage of NASA's space flight objectives, the Apollo Program.

Apollo Program

In 1961, President John F. Kennedy announced the singular, straightforward goal of the Apollo Program: to land a man on the Moon and return him safely to Earth before the end of the decade. This goal was achieved with the Apollo 11 mission in July 1969. Overall, the program included 29 astronauts, 12 of whom spent time on the lunar surface (Figure 1-3). The Apollo Program is among the greatest human achievements in science, engineering, and exploration in the 20th century.

Although the Apollo Program achieved its goals, it was not without tragedy. In January 1967, during prelaunch testing, a fire in the Apollo 1 capsule killed astronauts Gus Grissom, Ed White, and Roger Chaffee. The program was delayed while the fire was investigated and certain aspects of the Apollo capsule re-engineered. The hatch, for instance, was changed to allow the astronauts a quick escape route. In addition, the cabin environment was altered from 100 percent oxygen at launch to a mixture of oxygen and nitrogen; once in flight, the capsule environment was to convert to pure oxygen. Although an oxygen-only atmosphere facilitated life support system designs, it also contributed to the Apollo 1 fire.

Apollo was supported by a broad biomedical effort with three distinct goals (Johnston, 1975):

1. **Ensure the safety and health of crewmembers**. The Apollo flights highlighted health issues that had not been addressed earlier, foremost among them the potential for in-flight illness. During orbital flight, an astronaut could be recovered relatively quickly in the event of an in-flight emergency; during a lunar mission, circumnavigation of the Moon obviated this option. Therefore, a program was needed to minimize the likelihood of in-flight illness and to allow a reasonable measure of emergency treatment should an illness occur.

2. **Prevent contamination of Earth by extraterrestrial organisms.** A lunar landing raised for the first time the possibility of contaminating the Moon with terrestrial microorganisms or, of even more concern, the possibility of introducing unknown lunar microorganisms to Earth. To ensure that unwanted microorganisms were not exchanged, strict quarantine and decontamination procedures were implemented before and after each mission. A special Lunar Receiving Laboratory was constructed at NASA's Lyndon B. Johnson Space Center in Houston, Texas, to house astronauts and lunar samples for appropriate observation and research.

3. **Study specific effects of exposure to space**. The longer Apollo flights provided an opportunity to study the cardiovascular and bone adaptations observed during the Gemini Program in greater depth and to develop improved measurement techniques. Although the

operational complexity and rigorous demands of the Apollo Program limited the time available for biomedical experiments, the studies conducted did provide considerable information concerning cardiovascular function, metabolic balance, and microbial behavior. In addition, limited non-human biological investigations were conducted, including studies of radiation effects on the pocket mouse and the effects of heavy nuclei of galactic cosmic radiation on a number of biological specimens.

Biomedical observations during Apollo missions added vestibular disturbances to the inventory of significant biomedical findings pertaining to space flight (Dietlein, 1977). Soviet cosmonauts had reported motion sickness symptoms in flight as early as 1961 (Titov on Vostok-2), yet no symptoms of what would later be called space motion sickness had been reported by U.S. astronauts before Apollo. In the Apollo 8 and 9 flights, however, five of the six crewmembers suffered some degree of motion sickness, ranging from stomach awareness to actual sickness. In one case, the severity of the vestibular disturbance required postponement of portions of the flight plan.

Other significant biomedical findings from the Apollo Program confirmed Gemini results and helped to characterize these responses in further detail (Table 1-3). Of special interest was the absence of microorganisms in the materials returned from the lunar surface.

Skylab Program

The Skylab Program offered the first opportunity to study problems of habitability and physiological adaptation to space flight over extended periods. Composed of multiple components, Skylab was both a space habitat and an orbital laboratory. The orbital workshop (Figure 4-7) provided the primary on-orbit living and working quarters for crewmembers. Built from the third stage of the Saturn V booster rocket, the workshop was equipped to house three astronauts for up to three months. With a volume of approximately 294 m^3, the cylindrical workshop was huge in comparison with the Mercury, Gemini, and Apollo spacecraft (approximately 1 to 8 m^3). The additional room allowed astronauts to enjoy a lifestyle somewhat closer to Earth standards, with a radical improvement in freedom of movement (Figure 1-4). Skylabs-2, -3, and -4 lasted for 28, 59, and 84 days, respectively, permitting scientists to engage in detailed biomedical research on the physiological changes first observed in earlier programs.

The first Skylab crew was launched on May 25, 1973, and returned to Earth on June 22, 1973. While in orbit, the crew conducted solar astronomy and Earth resources experiments, medical studies, and five student experiments. During 404 orbits of the Earth, they conducted 392 hours of experimentation, in the process making three extravehicular activity (EVA) performances totaling six hours and 20 minutes.

Two other Skylab missions followed, with each crew increasing the previous crews' duration. In total, three astronaut crews occupied the Skylab workshop for 171 days and 13 hours and performed nearly 300 scientific and technical experiments. With the completion of the three Skylab missions, both the total hours in space and the total hours spent in EVA exceeded the combined totals of all of the world's previous space flights up to that time (Compton and Benson, 1983).

Skylab emphasized the intrinsic value of the human operator in space systems. A thermal problem caused by the loss of the micrometeoroid shield and the failure of the solar array wing to deploy properly would have rendered Skylab uninhabitable without direct human intervention (Belew, 1977). After rendezvous and survey of the damage, Skylab Commander Charles Conrad and Scientist-Pilot Joseph Kerwin spent nearly four hours outside the spacecraft repairing the damage. The task was especially complex, since the extent of the damage was unknown, the outcome was uncertain, and no special provisions had been made to facilitate EVA. Guided by ground staff, the Skylab team successfully released the solar wing and rectified the problem to the extent possible.

Skylab also demonstrated that, with sufficient attention to such issues as food service, waste management, and sleep arrangements, a spacecraft could provide satisfactory living and working quarters for long periods. By previous standards, only minor habitability problems were experienced in the Skylab orbital workshop. For example, sleeping compartments were not sufficiently isolated from each other and from the waste management compartment for optimum noise control. Mobility and restraint systems were also found to be major factors in perceived habitability in microgravity.

Skylab provided a wealth of biomedical data concerning the health and physiological responses of humans performing normal work activities and using countermeasures during long-term space missions. Skylab data were particularly useful in differentiating self-limiting physiological changes from those that continued throughout exposure to space flight. This information has since guided ground-based research as well as in-flight studies that seek to characterize human responses to the stresses of space flight.

The Skylab crews were monitored closely for signs of space motion sickness (Graybiel, 1981). During the first mission, none of the astronauts became motion sick, although one crewmember did take medication immediately after entry into orbit. No significant performance decrements were noted even during the physically demanding work of repairing Skylab damage before entering the orbital workshop. The second Skylab crew, who did not take prophylactic medication, experienced severe motion sickness symptoms. One crewmember became ill within an hour of achieving orbit—the earliest recorded appearance of motion sickness in orbital flight by American crews (Graybiel, 1981). The third Skylab crew took several precautions, including flying aerobatics on the day before the mission and following a schedule for taking anti-motion-sickness medication during the early days of the mission. Despite these measures, two crewmembers experienced motion sickness and one astronaut''s symptoms persisted well into the fourth day of flight.

Subjective reports from the three Skylab crews and vestibular experiments conducted during flight suggested that space motion sickness could not be predicted with the usual coterie of ground-based tests, but could be alleviated somewhat by the administration of prophylactic medications. Space motion sickness has remained a problem through the Space Shuttle era, however, and, despite advances in space pharmacology, the search for the optimum medication and schedule of administration continues (see Chapter 25).

Particular attention was given to cardiovascular changes in Skylab: orthostatic tolerance, electrical activity, and changes in heart size were all assessed. The response of astronauts to provocative orthostatic stress was examined in flight for the first time on Skylab. Crewmen were tested using a lower body negative pressure (LBNP) device before, during, and after all Skylab missions. The LBNP device was designed to impose orthostatic stress to the lower torso and legs for a period of 25 minutes through the application of a maximum negative 50 mmHg (50 torr) pressure. Although indices of reduced cardiovascular efficiency were again obtained, the observed cardiovascular deconditioning was found to stabilize after 4 to 6 weeks with no apparent impairment of crew health or performance (Dietlein, 1977). Cardiovascular deconditioning is currently regarded as a self-limiting adaptation to the reduced hydrostatic pressure differential imposed by microgravity.

Other areas of concern during Skylab were bone mineral loss and mineral balance in crewmembers. Preflight measurements of bone mineral content, using a photon absorptiometric technique, were compared with similar measurements taken at varying intervals after landing. No mineral losses were observed in the upper extremities, but some bone loss was noted in the lower extremities, specifically the *os calcis* (Vogel *et al.*, 1977). Data from the 84-day Skylab-4 mission led to the conclusion that the mineral losses incurred were comparable to those observed in bed rest studies (Dietlein, 1977). No evidence was found during these missions that the loss of bone mineral is self-limiting—even with the use of countermeasures—and this supposition has been recently confirmed during long Russian missions. Metabolic studies on Skylab showed a significant increase in the urinary excretion of calcium during flight in all crewmen measured. The loss continued throughout the period of flight, with no evidence of abatement during later stages. Significant amounts of nitrogen and phosphorus were also lost, presumably associated with loss of muscular tissue (Whedon *et al.*, 1977). Other evidence of muscle loss was obtained from anthropometric studies revealing marked decrease in leg volume, much of which was restored within 21 days of landing. About one-third of the loss was attributed to partial atrophy of the leg muscles due to disuse in microgravity, with the remainder caused by fluid loss (Whittle *et al.*, 1977).

The Apollo-*Soyuz* Test Project

The Apollo-*Soyuz* Test Project (ASTP) was conducted jointly by the United States and the Soviet Union as a means of promoting international cooperation in space ventures. The primary mission objective was to test rendezvous and docking systems that might be needed during international space-rescue missions. This required a proven ability to transfer crews between two spacecraft with dissimilar atmospheres. A second objective was to conduct a program of scientific experiments and technological applications. Both the Apollo and *Soyuz* spacecraft used in the ASTP were identical to those flown previously by each nation (Figure 1-5). A docking module for crew transfer was constructed specially for the mission.

The ASTP lasted for nine days, and the rendezvous and docking maneuver was completed successfully. The two spacecraft remained docked for two days while the crews exchanged visits. During the recovery phase, the U.S. crew was exposed to toxic gases, mostly nitrogen tetroxide, from inadvertent firing of the reaction control system during descent. These gases entered the command module through a cabin pressure relief valve that had been opened during the landing sequence. All crewmembers developed chemical pneumonitis as a result of the exposure and required intensive therapy and hospitalization at the Tripler Army Medical Center in Honolulu, Hawaii (Nicogossian *et al.*, 1977). Most of the planned postflight medical experiments were sacrificed to focus on clinical examination and treatment of the astronauts.

Despite the lack of postflight data, considerable information was obtained concerning the human reaction to space flight conditions. Electromyographic analyses of skeletal muscle function in leg extensor and arm flexor muscles showed that muscle dysfunction characteristics first observed upon 59 days of exposure to weightlessness in the Skylab-3 mission were also present after only nine days of exposure (LaFevers *et al.*, 1977). Short-term exposure also produced fatigue in muscle tissue, particularly in the antigravity muscles.

Duration of the Achilles tendon reflex was also measured after ASTP after general hyperreflexia had been observed in Skylab crewmen (Burchard and Nicogossian, 1977). As was the case in Skylab, two crewmembers showed a decrease in reflex duration within two hours after recovery relative to preflight measurements. In addition, all three ASTP crewmembers showed significant fine tremor, which was thought to reflect the effects of inhaling nitrogen tetroxide vapor (Nicogossian *et al.*, 1977).

The Space Shuttle Program

April 12, 1981, marked a new era in human space activities: the first successful orbital flight of the Space Shuttle, the world's first reusable spacecraft. The Space Shuttle consists of four components: a reusable orbiter mounted on an expendable, liquid-propellant tank, and two reusable solid rocket boosters. After a conventional launch, the orbiter operates as a spacecraft; upon atmospheric reentry, it sails like a glider to the designated landing site. Crewmembers experience a maximum chest-to-back 3g load during launch and less than 2g head-to-foot load during reentry. Up to eight crewmembers may be accommodated on a single mission, but the normal crew complement is seven.

The Space Shuttle is the first U.S. spacecraft in which astronauts operate at standard sea-level atmospheric pressure and composition. In comparison, Mercury, Gemini, and Apollo all operated at 0.33 atm and 100 percent oxygen while in flight. Although the atmospheric pressure aboard Skylab was also 0.33 atm, consideration of potential atelectasis and fire prevention safety over long periods dictated a compositional change to 70 percent oxygen and 30 percent nitrogen.

The Space Shuttle truly opened a new era in space exploration and utilization programs. The Shuttle program has launched numerous satellites and even repaired satellites in orbit, extending their service and enhancing their capabilities. One ailing satellite was retrieved and brought back to Earth for repair. Multiple EVAs, some lasting more than eight hours, have been conducted during the same missions.

Without question, the Shuttle greatly expanded the opportunity for human space flight. As of late 1999, 243 individuals have flown. Among other notable developments, Dr. Sally K. Ride became the first American woman to fly in space aboard STS-7 (June 1983) and STS-8 astronaut Guion S. Bluford became the first African-American to fly in space (August 1983). Since then, 31 female crewmembers have flown, including the first female Shuttle commander Eileen Collins in July 1999 on STS-93.

Crewmembers from many nations have participated in Space Shuttle activities (Table 1-4). The Shuttle was the first opportunity for scientists from universities and industries worldwide to participate in space-based investigations. The amount of scientific data obtained as a result of the Space Shuttle missions surpasses any scientific effort that any single nation has yet accomplished in space.

Space Shuttle and Spacelab

A key feature of the Shuttle has been the pressurized Spacelab module (Figure 1-6), a laboratory in which mission scientists can conduct experiments in Earth orbit. The Spacelab concept arose from the concept of equipping the orbiter's cargo bay with a "shirt-sleeve" laboratory in which the crew could operate instruments and perform experiments. Provided by the European Space Agency (ESA), Spacelab consisted of a pressurized, cylindrical laboratory with an external equipment pallet. The result was a highly flexible carrier system that was tailored and combined with other flight elements to meet the requirements of each mission (see Chapter 4).

Spacelab components first flew on the Shuttle in 1981 and flew 34 more times over the next 17 years for a total of 375 flight days. More than 750 Spacelab experiments resulted in over 1,000 referred articles, 2,000 talks and abstracts, and 250 masters and doctoral theses. Spacelab experiments were not only numerous, but they also drew from a wide international pool of participants: scientific hardware contributors and principal and co-investigators from 12 countries have contributed (Table 1-5).

A Spacelab module also flew to *Mir* as a visiting laboratory during the first U.S.-Russian Shuttle-*Mir* docking. Spacelab Life Sciences-1 and -2, along with Neurolab, were dedicated life sciences missions.

Data from these flights were supplemented by numerous investigations conducted on multidisciplinary Spacelab missions. Retired after the 1998 Neurolab flight, the Spacelab program provided a wealth of scientific and technical information on the physiological response to space flight.

The Spacelab experience has paved the way for research on the International Space Station. Two decades of conducting research in a laboratory environment 180 miles above the Earth has given the international space community experience in multinational cooperation and data dissemination, as well as improved research operations and results analysis.

Space Shuttle Post-*Challenger*

After 24 successful Space Shuttle flights, on January 28, 1986, the Space Shuttle *Challenger* was destroyed at liftoff by the explosion of a malfunctioning rocket booster, taking the lives of all seven crewmembers on board. This tragedy resulted in a hiatus of nearly three years in the U.S. human space flight program, with a total redesign of many components of the launch vehicles and provision of an early escape system for the crews. On September 29, 1988, the Shuttle program resumed with the launch of the Shuttle *Discovery*, its five crewmembers, and a communications satellite.

As of January 2000, 97 Shuttle flights have been completed, with 73 carried out since the *Challenger* accident. In its first 15 years of operation, the Shuttle carried approximately 2.3 million pounds of cargo and more than 700 major payloads into orbit for extramural researchers, commercial interests, other nations, and educational institutions. Its crews have also conducted more than 45 EVAs.

Shuttle capabilities for research and investigation enable the next stage in space medicine research. Functioning as an orbiting research laboratory, especially when carrying the Spacelab, the Shuttle has led to a more sophisticated scientific approach to the study of physiological adaptation and evaluation of countermeasures. For the first time, experiments can be conducted routinely on orbit to further investigate the effects of the space environment, particularly microgravity, on human physiology under conditions that cannot be duplicated on Earth. These investigations are complemented by ground-based research into changes in vestibular, cardiovascular, and hematologic function, as well as the effects of radiation and reduced apparent gravity on basic biological processes. Flight experiments have expanded our understanding of basic physiological mechanisms and established the time course of biological and biomedical changes during exposure to microgravity (see Chapter 11). In addition, through continuous in-flight observation of space crews, and via the validation and refinement of countermeasures, requirements have been expanded for human safety, health, and productivity in space. Assurance of astronaut health and productivity in turn provides sound foundations for a broader segment of the population to participate in space missions. The long-term clinical significance of risk factors that may be associated with repeated exposure to the space environment is also monitored and studied after flight (see Chapters 21 and 22).

Shuttle life sciences missions, which are currently housed in the middeck and have also been located in the Spacelab module, fall into three general categories:

1. The fully dedicated mission, in which the payload specialists are life scientists;
2. Missions with shared payloads, where various scientific disciplines are represented by onboard experiments; and
3. Small payloads that can be loaded into Spacelab or the orbiter middeck before launch, with minimal vehicle interfaces.

The results of various completed studies are described in greater detail in the following chapters.

Since 1989, biomedical scientists have worked to develop procedures that allow the safe extension of Space Shuttle missions up to 16 days. These extended duration missions—including two Spacelab Life Sciences (SLS) missions, Neurolab, and STS-95—have paved the way for expanded space medicine research on the ISS.

SLS-1, launched in June 1991, was the first mission dedicated entirely to understanding the physiological effects of space flight. An extensive series of biomedical experiments was conducted on crew members during the nine-day mission, and the results were compared with baseline data collected on the ground before and after the flight. Along with the human subjects, rodents and jellyfish also were on board to test their adaptation to microgravity.

In October-November 1993, aboard STS-58, NASA conducted the second dedicated Spacelab Life Sciences mission. Fourteen experiments were conducted in the areas of regulatory physiology, cardiovascular/cardiopulmonary, musculoskeletal, and neuroscience research. Eight of the experiments centered on the crew, while six investigations focused on 48 rodents carried on board. With the completion of her fourth space flight, Shannon Lucid accumulated the most flight time for a female astronaut on the Shuttle: 838 hours.

The April 1998 flight of STS-90, supported by NASA, international space agencies, and domestic partners (including the National Institute on Aging and the National Science Foundation), was a dedicated 16-day life sciences mission focusing on neuroscience research. Called Neurolab, the mission goals were four-fold:

1. To use the unique environment of space flight to study fundamental neurological processes;
2. To increase the understanding of the mechanisms responsible for neurologic and behavioral changes that occur in space flight;
3. To further life sciences goals in support of human space flight; and

4. To apply results from space studies to the health, well-being, and economic benefit of people on Earth.

More than 30 experiments conducted on Neurolab investigated specific areas of neuroscience and related areas: muscle physiology, neurophysiology, bone biology, cellular and molecular biology, pharmacology, endocrinology, and cardiovascular and pulmonary physiology.

In October 1998, at the age of 77, John Glenn, who had flown the first U.S. orbital mission in Project Mercury in 1962, served as a payload specialist on STS-95. Acting as test subjects themselves, the STS-95 crewmembers contributed to medical studies on sleep, balance, protein metabolism, and cardiovascular function. This research was conducted in collaboration with the National Institutes on Aging and was an initial attempt to ascertain whether space flight may serve as a model for aging research.

In addition to its research missions, the Space Shuttle will also play an integral role in the International Space Station (ISS) program. The Shuttle will be used to carry major American ISS components to orbit, rotate ISS crew, and carry logistics throughout the program life cycle. The first U.S. element, the Unity node, was successfully placed on orbit by the crew of STS-88 in December 1998 (Figure 1-7). The U.S. laboratory module, Destiny, will be launched in 2000 with five of 24 possible system racks already installed inside the module. Destiny will provide initial United States user capability in a wide range of disciplines, including advanced human support technology, biomedical research and countermeasures, gravitational biology, fluid physics, fundamental physics, materials science, and combustion science, among others.

THE EUROPEAN SPACE PROGRAM

The European Space Agency (ESA) formed out of the 1975 merger of the European Space Research Organization (ESRO) and the European Launcher Development Organization (ELDO). Fourteen countries are members of ESA (Table 1-6), with Canada accorded "cooperating state" status. Although headquartered in Paris, ESA is supported by specialized development centers throughout Europe: the European Space Research and Technology Centre (ESTEC) in Noordwijk, the Netherlands; the European Space Operations Centre (ESOC) in Darmstadt, Germany; the European Space Research Institute (ERSIN) in Frascati, Italy; and the European Astronaut Centre (EAC) in Cologne, Germany.

ESA's space flight experience began in 1968 with the launch of ESRO's first scientific satellite. Since that time, ESA has launched over 40 scientific, remote sensing, and communications satellites. In addition, ESA's successful series of Ariane launch vehicles have carried hundreds of satellites into orbit for multiple countries.

ESA entered the human space flight arena in 1973 with the development of Spacelab, a multipurpose human space laboratory flown on the Space Shuttle. Between 1981 and 1998, components of Spacelab flew on the Space Shuttle 35 times and flew to the Russian space station *Mir* twice.

ESA astronauts have played an active role in life sciences research on the Space Shuttle. As of late 1999, ESA astronauts have flown on 15 Shuttle missions beginning in 1983 (Table 1-7). Thirteen ESA astronauts have also stayed aboard Soviet and Russian space stations (Table 1-8).

In addition to Spacelab, several other pieces of European hardware are essential to space life sciences research. Microgravity research facilities designed within the European Microgravity Research Programme (EMIR) have flown on Spacelab missions, sounding rockets, Russian retrievable carriers, *Mir*, the European recoverable platform *Eureca*, and Spacehab **[is this Spacelab?]**. EMIR Spacelab life sciences facilities include Biorack (cell biology), Anthrorack (human physiology), and the Glovebox (equipment preparation). ESA also developed various physiology facilities for *Mir*, as well as the Biopan and Biobox cell biology facilities carried on the retrievable Russian carrier Foton.

Although the 1998 Neurolab mission marked the final flight of Spacelab, ESA's involvement in human space flight and life sciences investigations is far from over. Many of the participating organizations, especially France's Centre National d'Etudes Spatiales, the Netherlands Agency for Space Programs, the Austrian Space Agency, and the German Aerospace Research Establishment, maintain active life sciences research programs. Furthermore, as one of the international partners in the ISS program, ESA will have access to its state-of-the-art on-orbit laboratories for conducting life science investigations.

ESA's direct contributions to the ISS include flight elements and transport vehicles. ESA's first contribution to the ISS is Columbus, a pressurized, habitable multi-purpose microgravity laboratory scheduled for launch in 2003. One of Columbus's modules, the Biolab facility, will be dedicated to the study of gravitational and radiation biology, while the module itself will also act as the main workplace for ESA's on-orbit astronauts. ESA will also construct and operate the Automated Transfer Vehicle (ATV). The ATV, to be launched on ESA's Ariane 5, will service the ISS for cargo delivery, refueling, reboost and attitude control, and waste removal. The first of at least eight ATV launches is scheduled for 2003.

In addition to its direct contributions to the ISS, ESA has also signed bilateral cooperation agreements with other ISS partners. ESA has signed an agreement with the Russian Space Agency (RSA) to provide the data management system for the Service Module, as well as the European Robotic Arm (ERA), a piece of hardware to be used for assembly and maintenance of the Russian segment of the ISS. ESA has also signed a cooperative agreement with the Japanese National Space Development Agency (NASDA) to provide cooler and freezer equipment for the Japanese Experiment Module *Kibo*.

THE JAPANESE SPACE PROGRAM

NASDA was established on October 1, 1969, to promote the peaceful development and use of space. Since that time, NASDA has developed a significant technological base in support of both crewed and robotic space missions. NASDA's satellite program began in 1975, with the launch of the first Engineering Test Satellite. Since then, NASDA has launched over 30 communication, remote sensing, and meteorological satellites. Several of NASDA's satellites (e.g., the Space Flyer Unit), along with experiments flown on Spacelab missions, are part of NASDA's growing efforts in microgravity and life sciences research. In addition, NASDA has developed several launch vehicles, including the H-II and the HOPE-X (an uncrewed craft that will validate new technologies for reusable launch vehicles).

NASDA enhances its robotic research with its human space flight program. Although not an official NASDA astronaut, journalist Tohiro Akiyama became the first Japanese to fly in space in 1990. Akiyama's eight-day stay on *Mir*, sponsored by the Tokyo Broadcasting System, marked the first commercial flight to the Russian station. Officially, NASDA has selected and trained five astronauts as payload and mission specialists.

Like ESA, NASDA has also played an integral role in the Shuttle's life sciences research program (Table 1-9). Spacelab-J, flown on STS-47, was a cooperative effort between NASDA and NASA, with a focus on fundamental materials and life sciences. As part of this international mission, the crew (including payload specialist Mamoru Mohri, the first NASDA astronaut) performed 13 life science and 22 material science experiments developed by NASDA, in addition to NASA experiments. NASDA astronaut Chiaki Mukai's two missions have both had a life science focus. Her first flight, the second International Microgravity Laboratory (IML-2) on STS-65, was designed as an extended duration orbit mission focusing on the cardiovascular, nervous, and musculoskeletal systems; Mukai's second flight, STS-95, examined the effects of space flight on the human body and their similarities to the aging process.

Current and future NASDA plans in the space life sciences arena focus on a continued human presence in space. In addition to the 21st century goals of a lunar base and a national space station, NASDA is also a partner in the ISS program, providing both station elements and resupply craft. The Japanese Experiment Module, renamed *Kibo* ("Hope" in English), will be Japan's first crewed space activities facility. *Kibo* is a multi-user facility for long-duration microgravity research. A second NASDA ISS element, the Centrifuge, is a life sciences research facility dedicated to the quantitative investigation of gravity's effects on biological systems. Experiments carried out in the three components of the Centrifuge will cross a wide range of life science sub-disciplines, including hematology, immunology, neuroscience, plant physiology, and radiobiology.

In addition to *Kibo* and the Centrifuge, NASDA will also provide the ISS with a resupply ship. The HTV (H-II Transfer Vehicle) can carry up to seven tons of supplies to the ISS. Both the launch of *Kibo* and the demonstration flight of the HTV are scheduled for 2002. The components of the Centrifuge will be launched to the ISS separately beginning in 2001, with full integration of the entire assembly by 2004.

Current NASDA training facilities are centered around the needs of the ISS. The Weightless Environment Test Building at Tsukuba Space Center houses a simulation tank spacious enough for a full-sized mockup of *Kibo*. NASDA uses the tank for EVA simulation tests and basic training of ISS astronauts. In addition, the Astronaut Training Facility (ATF), scheduled for full-scale operation in 2004, will serve as the center for astronaut selection, training, health care, and medical research. ATF facilities include:

- an isolation chamber to study the mental and physiological stresses an astronaut in the isolated, multicultural ISS environment may face;
- a hypobaric chamber to simulate low atmospheric pressure, allowing astronauts to experience—and react to—pressurization system failure before they reach orbit;
- a health care facility for astronaut selection, training, and health care;
- vestibular function research facilities to investigate the mechanism for and countermeasures against the spatial disorientation experienced in microgravity;
- bed rest study facilities to examine and develop countermeasures against the bone loss and muscle atrophy that occur in microgravity; and
- additional space medicine research facilities.

THE CANADIAN SPACE PROGRAM

The Canadian Space Agency (CSA), a fourth partner in the ISS effort, was established by the Canadian Parliament in 1989, with the mandate to promote the peaceful use and development of space for the societal and economic benefit of Canadians. The CSA coordinates all sectors of the Canadian space program and directly manages five of these sectors: Space Systems, responsible for Canada's ISS program; Space Operations, which includes a satellite testing facility and operation of the first Canadian Earth observation satellite, Radarsat; the Canadian Astronaut Office; Space Sciences, which oversees research in space life sciences, atmospheric science, astronomy, microgravity, and solar-terrestrial relations; and Space Technologies, which works in conjunction with Canada's space industry and also leads the interaction between CSA and ESA.

The CSA has built a Canadian presence in the arenas of human space flight activities and space life sciences research. As of June 1999, nine Canadian astronauts have flown on Space Shuttle missions, including the first logistics flight to the ISS (Table 1-10). Several Shuttle missions—including Neurolab, STS-95, LMS-1, and IML-2—have carried CSA space life sciences payloads. The CSA has also sponsored sleep-immune function and radiobiology experiments on *Mir*.

Canada will continue its human space flight and space life science research programs on the ISS. One of Canada's most essential contributions to the ISS program is the Mobile Servicing

System (MSS). The MSS—used for Station assembly and maintenance, equipment and supply movement, satellite capture and release, EVA activities, and payload maintenance—is actually a three-part assembly. The Space Station Remote Manipulator System (SSRMS), or Canadarm, is a more advanced version of the Canadian-built robotic arm used on the Space Shuttle. Seventeen meters long when fully extended, the Canadarm is capable of handling large payloads and assisting in Space Shuttle dockings. The Canadarm can be attached to several points along the ISS exterior. The second part of the MSS, the Mobile Base System (MBS), is a mobile work platform oriented along the length of the ISS to provide lateral mobility for the Canadarm. The final element of the MSS, the Special Purpose Dexterous Manipulator (SPDM, or Canada Hand), is a two-armed robot that can be used for delicate assembly and maintenance tasks. The MSS will be installed in several parts beginning with the installation of Canadarm in July 2000, followed by the MBS in 2001 and the SPDM in 2003.

THE SOVIET/RUSSIAN HUMAN SPACE PROGRAM

The Soviet Union began the space age in October 1957 with the launch of Sputnik-1. This remarkable achievement was followed within a month by the launch of Sputnik-2, carrying a dog named Laika. The advent of *glasnost* lifted the veil of secrecy that had once shrouded the Soviet space program and revealed that the seemingly well-organized, fast-maturing space program of the early 1960s was affected by the early setbacks of the "Moon race" and political strategy. Some of the technology developed for a human lunar program during the late 1960s and early 1970s was converted for use with Earth-orbital space stations and is still in operation today. For the past two decades, maintaining space stations and extending the duration of human flight have been the near-term objectives of the Soviet space program; their long-range plans to send humans to Mars have been affected seriously by the recent financial difficulties associated with the dissolution of the Soviet Union.

The Vostok Program

The era of human space flight began with the April 12, 1961, launch of Yuri A. Gagarin aboard Vostok-1 (Figure 1-8). The two-year preparation for this historic mission included two suborbital and six orbital unmanned test flights, some of which carried dogs. Critical systems necessary to ensure safe and successful human flights were validated, including spacecraft and space suit life support, orientation and attitude control, reentry retrorockets, heat shields, ejection seats and recovery apparatuses. The Vostok spacecraft was designed to be under automatic control, but cosmonauts could take over in the event of autopilot failure (Newkirk, 1990).

As in the U.S. program, the first Soviet cosmonauts were recruited from military test pilots. On March 14, 1960, a group of 20 cosmonaut candidates began the first training program, which included lectures in aviation medicine, spacecraft design, and orbital mechanics. Six were chosen from this group for advanced training, including work with the Vostok spacecraft, and only 12 of the original 20 candidates actually made space flights. Five women joined the cosmonaut team in 1962, but only Valentina Terishkova actually flew in space, aboard Vostok-6 (Clark, 1988).

The five Vostok missions gathered invaluable data about the reaction of the human body to the microgravity environment. Early Vostok missions monitored cosmonauts via ECG, pneumography, and television camera. When Gherman Titov experienced the spatial disorientation and vestibular symptoms later known as space motion sickness on Vostok-2, subsequent missions were postponed while physicians attempted to design experiments and hardware to characterize and evaluate this new phenomenon. As a result, electro-oculography, electroencephalography, skin galvanic resistance tests, and sensory motor performance evaluations were added to the medical monitoring program of later flights. The Vostok program also validated rendezvous technologies and set endurance records.

The Vostok flights proved that humans could survive the rigors of space flight for up to five days. Space motion sickness symptoms did not affect the successful completion of the missions. Biomedical monitoring during flight and extensive testing after return failed to uncover any pathological disturbances. Postflight orthostatic intolerance was noted in some of the crewmembers but was not considered significant. A seventh Vostok flight, which was to include a week-long evaluation of in-flight physiological adaptation, was considered but was canceled in favor of developing other capabilities for future programs (Clark, 1988).

The Voskhod Program

Voskhod was an interim program devised to maintain the Soviet presence in space and demonstrate some of the capabilities required for human lunar missions and Earth-orbiting space station operations. The *Soyuz* program, originally envisioned to follow Vostok, would include new spacecraft capable of housing several crewmembers, orbital maneuvering, rendezvous and docking, long-duration flight, and EVA; this spacecraft, however, would not be flight-ready until at least 1966. The prospect of a three-year hiatus between 1963 and 1966, during which the American Gemini Program was scheduled, prompted the development of the Voskhod spacecrafts from upgraded Vostok technology.

Three flights were planned for the Voskhod program: a short flight with three crewmembers, a short flight that included an EVA, and a two-week mission (Clark, 1988). The two-week mission was subsequently canceled, but the spacecraft intended for that flight flew as a biosatellite (Kosmos-110) with two dogs and spent 22 days in space. The conversion of the Voskhod spacecraft into a biosatellite initiated a series of research flights that continue today.

With only two human flights during the Voskhod era, the program nonetheless demonstrated key capabilities required for subsequent programs in addition to reaching several more precedents in space travel. On Voskhod-1, for instance, Dr. Boris Yegorov became the first physician in space and conducted a series of pulmonary, vestibular, and circulatory experiments.

In addition, Aleksei Leonov conducted the first EVA—lasting only 12 minutes—during Voskhod-2 in 1965 (Figure 1-9).

The Early *Soyuz* Flights

The *Soyuz* spacecraft was originally envisioned as part of a human lunar landing program, with modifications planned for circumlunar flight (Mishin, 1990). Carrying three crewmembers, *Soyuz* was capable of extensive orbital maneuvering, rendezvous and docking, extended independent flight, and EVA via its orbital module. Several robotic tests of the *Soyuz* were completed in late 1966 and early 1967, and although serious flaws were detected in critical systems, the spacecraft was approved for human flight.

The first mission of the *Soyuz* program was to have been a "space spectacular" (Nikishin, 1992). The launch of *Soyuz*-1 with a single crewmember was to be followed 24 hours later by three cosmonauts aboard *Soyuz*-2. After rendezvous and docking, two of the *Soyuz*-2 crew were to don space suits and transfer by EVA to *Soyuz*-1. The two spacecraft were then to separate and return to Earth.

Soyuz-1 was launched on April 23, 1967, with Vladimir Komarov on board. Because electrical trouble arose almost immediately, the *Soyuz*-2 launch was called off and Komarov was told to return. Overcoming serious attitude-control problems, Komarov made a successful manual reentry only to have tragedy strike. The primary parachute failed, and the backup parachute became tangled in the drogue parachute. Komarov was killed when the capsule crashed at over 300 km/h (Nikishin, 1992).

The *Soyuz*-1 tragedy halted Soviet human flights for 18 months. Following a redesign, manned flight resumed in October 1968 when *Soyuz*-3 rendezvoused with the unmanned *Soyuz*-2. In January 1969, the *Soyuz*-4 and -5 crews completed the rendezvous, docking, and EVA transfer that had initially been planned for April 1967.

The successes of the *Soyuz*-4 and -5 missions brought to fruition several of the critical technological steps required for a human lunar landing. The most important element, however, a booster powerful enough to launch components toward the Moon, proved troublesome (Mishin, 1990). A month after the *Soyuz*-4 and -5 missions, the N-1 booster exploded 70 seconds into its first unmanned test flight. Three more unmanned attempts to launch the N-l in 1969, 1971, and 1972 also failed before the program was canceled in 1974.

While human *Soyuz* missions continued, the emphasis shifted toward using the vehicle as a means of transporting crews to and from Earth-orbiting space stations. *Soyuz*-6, -7 and -8 were flown as a triple flight in October 1969, putting seven cosmonauts in space simultaneously.

The final flight of the early *Soyuz* series, *Soyuz*-9, took place in June 1970. During this 18-day mission, hardware and techniques to be used on upcoming space stations were evaluated, and extensive biomedical monitoring was employed to assess the specific effects of weightlessness. Tests included electrocardiographic and blood pressure monitoring, tests of vision and hand grip strength, and collection of blood and urine samples for postflight analysis. Although the cosmonauts exercised during flight in an attempt to counteract the effects of weightlessness, they still experienced orthostatic intolerance and muscle weakness upon return and required nearly two weeks to recover completely (Kalinichenko *et al.*, 1970). This outcome sparked renewed concern about the outlook for long-term human missions, prompting a vigorous search for countermeasures to physiological deconditioning in the next phase of the Soviet space program.

Almaz and Early *Salyut*

Like their American counterparts, Soviet space advocates had long pressed for the development of a space station. As early as 1962, Soviet engineers proposed a space station comprised of modules launched separately and brought together in orbit. These first-generation space stations had one docking port and could not be resupplied or refueled. There were two types of early Soviet stations: the secret *Almaz* military stations and a public set of *Salyut* civilian stations (Launius, 1998).

The first Soviet space station program, Almaz, was approved in 1967 (Afanasiyev, 1991). It had three parts: the Almaz military surveillance space station, Transport Logistics Spacecraft for delivering crew and cargo, and Proton rockets for launching both. All of these spacecraft were built, but none was used as originally planned. To counter American success with Apollo, Soviet leaders directed that Almaz hardware be transferred to the civilian *Salyut* program so that the Soviet Union could recover a measure of international prestige with a spectacular public success.

This space station weighed about 18,000 kg, and would support a two- to three- person crew brought to the station by a separate space vehicle. This crew would conduct research and then use the transport vehicle's reusable reentry capsule to return to the U.S.S.R. The primary goal of the Almaz space station program was military reconnaissance, although other investigations were also included. By 1970 the space station was ready for launch, but the transport vehicle's development was delayed in part by the inability to human-rate the Proton rocket. During this delay, the space agency decided to modify the space station and to use the *Soyuz* spacecraft as a crew transport vehicle. The modified space station program was to be called *Salyut*; subsequent Almaz stations were also called *Salyut* in order to conceal the existence of two separate programs.

Salyut-1 was launched atop a Proton rocket on April 19, 1971, becoming the world's first space station (Figure 1-10). Following *Soyuz*-10's inability to successfully dock with the station, the crew of *Soyuz*-11 became the first crew to occupy a space station on June 6, 1971 (Vasiliyev *et al.*, 1973). During working hours of their 23-day stay, they wore "Penguin" suits designed to counteract the effects of weightlessness on their skeletal musculature (Figure 26-9). Planned daily exercise using a treadmill and bungee-cord devices was curtailed because of vibration affecting the station's structural integrity. Hand-grip strength and on-board radiation levels were measured. Orthostatic tolerance was monitored using the "Chibis" LBNP device. Blood and urine samples were collected during flight for postflight analysis.

After their mission, the *Soyuz*-11 crew undocked from *Salyut*-1 and performed a nominal automatic reentry and landing sequence. But recovery teams arriving at the capsule found the cosmonauts still in their couches, dead. A pressure equalization valve had opened accidentally shortly after the orbital and descent modules separated. The crew, who were not wearing pressure suits, died as a result of the sudden depressurization. The *Soyuz*-11 accident resulted in a hiatus in Soviet human flight activity while the cause was identified and corrected; the process took approximately one year. The redesigned *Soyuz*, reconfigured to carry only two crewmembers wearing full pressure suits, was tested without a crew in June 1972.

The next three stations, including the first Almaz station, failed to reach orbit or maintain a habitable environment. The first successful Almaz station, *Salyut*-3, was launched on June 25, 1974. *Salyut*-4 and *Salyut*-5 (also an Almaz station) followed in December 1975 and June 1976.

The biomedical aspects of *Salyut*s-3, -4, and -5 each built on the work of the preceding missions. Investigations covered multiple facets of human physiology: cerebral circulation, heart rate and rhythm, respiration rate, central and peripheral hemodynamics, and vestibular function. Countermeasures developed during *Salyut* missions, including the four-day exercise cycle and LBNP device, are still in use today.

Salyut-6 and *Salyut*-7

Extending flights beyond two months had been hampered by limitations on the amount of consumable items and the on-orbit lifetime of the *Soyuz* spacecraft. These obstacles were overcome by adding a second docking port to the station. Unmanned cargo ships could bring food, water, oxygen, and propellant to an occupied station; other crews could also be brought to the station for crew exchanges or visits.

With the second-generation stations, the Soviet space station program evolved from short-duration to long-duration stays. These stations had two docking ports to permit refueling and resupply spacecraft. A second docking port also meant long-duration resident crews could receive visitors. Visiting crews often included cosmonaut-researchers from Soviet block countries or countries sympathetic to the Soviet Union. Vladimir Remek of Czechoslovakia, the first space traveler from neither the U.S. or the Soviet Union, visited *Salyut*-6 in 1978.

The first space station with two docking ports was *Salyut*-6, launched on September 29, 1977, and operational until 1982. Five two-man crews completed flights lasting 96, 140, 175, 185, and 75 days between 1977 and 1981. In addition, 13 crews completed shorter (two- to 13-day) flights, although two were aborted after docking failures. Nine cosmonauts from Soviet block countries flew as members of the visiting crews (Table 1-11). The Soviets accumulated more than three years of flight time and five hours of EVA during the *Salyut*-6 program alone, establishing new endurance records.

By the end of the *Salyut*-6 program, the replacement *Salyut*-7 station was already in orbit, having been launched on April 19, 1982 (Figure 1- 11). Similar to its predecessor but with upgraded systems, this station was home to 10 cosmonaut crews that included six long-duration crews, one of which set a record 237 days in orbit. The Soviet Union expanded its crew significantly during the operational life of *Salyut*-7, inviting France and India to send their own crewmembers (Table 1-11).

Salyut-7 included extensive EVA activity. Some of this was repair work: first in 1984 to fix a ruptured propellant line and again in 1985 to restore power and attitude control to the station. Cosmonauts on *Salyut*-7 also conducted EVAs to add solar cells and test construction techniques. In all, more than 47 hours of EVA were completed, including the first EVA by a woman, Svetlana Saviskaya, in 1984.

As mission duration increased during the *Salyut*-6 and -7 programs, biomedical operations focused on improving health monitoring techniques and countermeasures (Gurovskiy, 1986; Anonymous, 1988). Among the several innovations in these programs were the regular in-flight monitoring of leg volume and body mass changes, the use of thigh-occlusion cuffs to minimize the effects of headward fluid shifts early in flight, muscle electrostimulation to minimize muscle atrophy, and a new noninflatable anti-*g* suit worn on the legs and abdomen during reentry and after landing to reduce orthostatic intolerance. In-flight echocardiography was first performed on *Salyut*-7 with French and Soviet instruments. During the 237-day flight aboard *Salyut*-7 in 1984, Dr. Oleg Atkov conducted numerous biomedical studies, including echocardiography using an instrument of his own design. A rehabilitation program was also established for cosmonauts returning from long-duration flights (Krupina *et al.*, 1981).

Two *Salyut*-7 missions included other events of medical significance. The first involved a crewmember who developed right lower-quadrant pain six months into the flight (Lebedev, 1988). The condition was diagnosed remotely as ureterolithiasis, although acute appendicitis was also considered. His symptoms persisted for several days and then resolved, and the flight continued without further incident. The second event, a case of chronic prostatitis that left the cosmonaut unable to perform his duties, caused the return of the entire crew (Tarasov, 1985; Goncharov, personal communication).

Salyut-7 was abandoned in 1986 and reentered Earth''s atmosphere over Argentina in February 1991. The *Salyut*-6 and -7 programs, despite temporary setbacks, verified that humans could live and work productively in space for up to eight months and function upon return to Earth. The advances of these programs paved the way to a permanent human presence in space and were immediately succeeded by the operation of the Soviet Union's first long-duration space station, *Mir*.

The *Mir* Complex

The *Mir* space station, launched on February 19, 1986, was designed to be the core of a permanently occupied complex with an expected lifetime of at least five years. Derived from earlier *Salyut* stations, the *Mir* core module had a five-port docking compartment at the front of the station that greatly expanded its capabilities (Figure 1-12). Another docking port at the rear of the station was available for the docking of *Soyuz*, additional space station modules, or *Progress* resupply craft. *Mir*'s core module contained the principal crew work and rest stations, including biomedical instrumentation, exercise equipment (treadmill and bicycle ergometer), and hygiene facilities, as well as the control center for the complex.

The *Mir* complex supported 29 crews, most of which remained onboard four to six months, although the longest missions lasted over one year. Twenty-five international crewmembers visited the station on shorter flights (Table 1-11). With the exception of approximately four months in 1989, the *Mir* complex has been occupied continuously since February 1987. Numerous maintenance, repair, and construction tasks, as well as new-technology demonstrations, have been carried out in more than 70 EVAs totaling over 300 hours.

The evolutionary approach in the development of *Mir*, the world's first permanently inhabited space station, allowed design changes to be made within its lifetime. Its modular construction permitted new elements to be attached on either a temporary or a permanent basis (Table 1-12). In addition to equipment carried on *Salyut* missions, upgraded biomedical hardware on *Mir* includes an echocardiograph and an automated capillary blood analyzer.

A medically significant event took place on *Mir* in 1987, two months into a planned 11-month mission (Gazenko *et al.*, 1990). The ECG of one crewmember revealed a series of premature atrial contractions with episodes of trigeminy during a particularly stressful EVA; on a subsequent treadmill test, the same crewmember showed pronounced tachycardia with numerous supraventricular extrasystoles. No symptoms were present during either episode.

Antiarrhythmic medication and reduction of the crewmember's work load appeared to control the arrhythmia, and his ECGs during two subsequent EVAs two months later were normal. Two weeks later, however, the arrhythmia returned during physical exercise and was again asymptomatic. As a precaution, the crewmember was returned to Earth during a previously scheduled visiting flight six months into the mission. Postflight evaluations revealed no arrhythmia, and the crewmember has been returned to flight status since.

Mir began another phase of its service life with the signature of a 1992 agreement between Russia and the United States for joint space investigations (see following section). Under this agreement, Russian cosmonauts flew on several missions aboard the Space Shuttle (Table 1-4) and American astronauts undertook extended stays on the *Mir* (Table 1-11). In 1994, Sergei Krikalov became the first Russian to fly on the Space Shuttle. One year later, U.S. astronauts began flying aboard *Mir*, traveling to and from the space station aboard both Russian *Soyuz* spacecraft and the American Shuttle. Also in 1995, the Space Shuttle docked with *Mir* for the first time and an ambitious program of life sciences experiments was conducted jointly by the two space agencies (Figure 1-13). The results of many of these experiments will be discussed in later chapters.

In the latter part of the 1990s, Russia announced plans to abandon *Mir* in 1999 and to focus all of its efforts on the construction of the ISS. The Russian government nevertheless issued a decree on January 22, 1999; this document extended the life of the *Mir* space station through 2002 via private commercial funds, and no longer required the use of government funds that once supported station operations.

The necessary funds, however, were not found. On August 27, 1999, Jean-Pierre Haignere, Viktor Afanseyev, and Sergei Avdeyev left *Mir* and returned to Earth, becoming the final cosmonauts to stay on the station. *Mir* had been in space for over 13 years and completed more than 77,000 orbits. Eventually, *Mir* will be edged closer to the Earth, after which it will enter the atmosphere and splash down in the ocean.

The NASA/*Mir* Phase I Program

The 1993 decision to include Russia as an ISS partner presented NASA with a singular opportunity. Russia entered the ISS partnership with a unique set of experiences and capabilities in long-duration human space flight. Accordingly, a three-phase development process for the ISS was initiated. Phase I of this process was designed to decrease the risks associated with assembling, operating, and conducting research on the ISS: it consisted of a series of Space Shuttle-*Mir* rendezvous flights and the long-duration stays of seven NASA astronauts on *Mir*. The program also provided for nine Russian cosmonauts to fly on the Space Shuttle.

Phase I facilitated the later stages of ISS development through fulfillment of four primary goals:

1. Reduce the risks associated with developing and deploying the ISS;
2. Garner operational experience for NASA on long-duration orbital missions;
3. Conduct peer-reviewed, precursor scientific research in preparation for the ISS; and
4. Learn how to work in a multicultural environment.

As part of the Phase I program, the United States helped finance and equip the last two *Mir* modules, *Spektr* and *Priroda*, with scientific instruments. These modules were launched to *Mir* in 1995 and 1996, respectively. The United States also funded the construction and delivery (via the Space Shuttle) of additional solar arrays for the Russian station to supply more power for experiments.

The successful execution of the Phase I program required precise working coordination among a broad array of Russian and American support elements. *Mir* was supplied by three separate space vehicles; it was equipped with both Russian and American research facilities, including hardware provided by other international partners, and supported a crew that traveled to and from the station via the Space Shuttle or the *Soyuz*. Russian and American technical personnel coordinated between two separate mission control centers, one in Russia and one at the Johnson Space Center in Houston, Texas.

The last of the Phase I Shuttle flights picked up Dr. Andrew Thomas in June 1998, at which time American astronauts had spent more than 975 days on *Mir*. This record exceeded the total time spent in space by the Space Shuttle fleet in its first 17 years of operation.

U.S. astronauts participated in several EVAs conducted solely from *Mir* (as opposed to those conducted from the Shuttle during docked operations). Dr. Jerry Linenger was the first American to use the Russian Orlon EVA suit as he deployed U.S. science equipment and gained valuable experience with Russian EVA hardware and procedures. Dr. Michael Foale participated in an important space walk to assess the damage to *Spektr* caused by the June 1997 collision between the station and a Russian *Progress* vehicle. Dr. David Wolf took part in a *Mir* space walk to accumulate further experience with the Russian EVA suit and to conduct U.S. research. As a precursor to Dr. Foale's EVA, joint criteria and guidelines necessary to certify the safety of an unplanned EVA were developed. These experiences prepared the space community to some extent for the multinational endeavor of on-orbit ISS assembly.

Several challenging situations on *Mir* during the course of Phase I operations led to a number of hardware, software, and procedural changes for the ISS. For example, a February 1997 fire aboard *Mir* caused NASA to re-evaluate ISS fire control options. *Mir* operations demonstrated that a temporary shutdown of the station ventilation system could help prevent a fire from spreading. ISS software was subsequently modified to allow a temporary, single-command ventilation shutoff between modules. In addition, the incident made mission planners more cognizant of the location of critical hardware such as medical kits and fire extinguishers.

The depressurization of the *Spektr* module after a collision with a Russian *Progress* vehicle in June 1997 validated U.S. craft design (which lacked cables running though open hatches) and demonstrated the importance of maintaining clear station passageways. In the incident, *Mir* crew members had to rush to disconnect cables that connected the leaking *Spektr* module to the rest of the station before they could close the hatch; *Spektr*'s depressurization led to the redesign of some critical Russian ISS components. The experience also emphasized the need for astronauts to have portable life-support sensors capable of monitoring total pressure, oxygen content, and similar parameters in the spacecraft environment.

Researchers have also found that some corrosion on the inside of *Mir* resulted from otherwise benign contact between two dissimilar metals. When humidity levels on *Mir* are high, different metals can react corrosively at their points of contact. Protective coatings have been added to some ISS cooling lines to prevent similar problems on the international station.

The Phase I science program provided the international scientific community access to a research environment similar in many ways to the ones that will be found on the ISS. Researchers used the *Mir* opportunity to familiarize themselves with operational protocols and techniques, to test equipment, and to conduct experiments as precursors to ISS research. Many of the American researchers had flown experiments on the Shuttle and on Spacelab missions. Often, their goal was to conduct experiments on *Mir* similar to their previous Shuttle work, in order to identify the differences in results between short-duration and long-duration space flight, and to complement their ongoing ground-based work. In addition, Phase I gave scientists a "hands-on" preview of day-to-day scientific operations in a long-duration, orbiting research facility. About 150 peer-reviewed investigations, spanning a wide variety of research disciplines and experimental programs, were conducted aboard *Mir* as part of the Phase I research program. A NASA strategic planning group coordinated both the Space Shuttle and *Mir* research elements for the Phase I program.

Of particular note are Phase I science results that indicated that NASA's model for the trapped radiation environment around Earth underestimated the radiation exposure risk to astronauts during periods of high solar activity and overestimated the levels during periods of low solar activity. NASA used the Phase I measurements, together with Shuttle data, to develop corrections to the existing radiation model, improving the average accuracy of radiation health risk predictions. Data also indicated that the South Atlantic Anomaly, a portion of the Van Allen radiation belts that dips down into the Southern Hemisphere, has shifted since last measured during the Skylab program. NASA subsequently worked to improve planning and scheduling practices to minimize astronaut radiation exposure during extravehicular activities around the ISS.

Russian Contributions to the ISS Program

Russia's *Zarya* ("Sunrise" in English) control module was the first ISS component to be placed in orbit. Launched on a Russian Proton rocket in November 1998, *Zarya* provided propulsion, communications, and power for the attached Unity module until the launch of the second Russian element, the *Zvezda* service module, in late 1999. The service module, similar in design and layout to the core module of *Mir*, will provide early crew living quarters, life support and data processing equipment, flight control, communications technologies, and propulsion systems and is intended to later replace or enhance many of *Zarya*'s functions. Eventually, *Zarya* will be used primarily for its storage capacity, while the service module will remain the functional center of the Russian segment of the ISS.

Along with the early modules, original plans for the ISS call for Russia to supply several other elements. Two research modules and a science power platform make up part of Russia's contribution to ISS research. In addition, Russia is also scheduled to provide logistics transport vehicles, as well as *Soyuz* spacecraft for crew return and transfer.

THE PRACTICE OF SPACE MEDICINE TODAY

Space medicine researchers continue to address issues concerning physiological adaptations to the space environment (both short- and long-term) and the development of effective, reliable countermeasures against these adaptations. Bone and muscle loss, neurovestibular dysfunction, cardiovascular deconditioning, and changes in to the immune, metabolic, and endocrine systems have long been noted as elements of the human body's response to microgravity. Although countermeasures that include controlled diets and a varied exercise program have been in place for years on both American and Soviet/Russian missions, current methods are not sufficient to maintain pre-flight levels of health throughout an extended mission. Today, researchers world-wide are working to develop the knowledge base, technology, and procedures necessary to sustain long-duration missions to low-Earth orbit and beyond.

NASA and National Institutes of Health (NIH) workshops have indicated that there are parallels between aging on Earth and some of the accelerated physiological changes observed in spaceflight (see Tables 1-3 and 1-5 and the following chapters). Some of the changes to the neurosensory, neuromotor, musculoskeletal, and cardiovascular systems seem to be reversible even after long-duration missions. Others, such as full recovery of lost bone mass and strength following return to Earth, require validation. Yet in a recent review of select parameters associated with aging in astronauts, we have observed an inconsistency in minimal oxygen consumption with exercise (VO_2) despite continued engagement in regular physiological activities (Nicogossian et al. 1999). In addition, a recent discovery that gravity can up- or down-regulate certain gene expressions has changed the way we view spaceflight responses in physiology.

These findings are important indicators that long-term residence in a low-gravity environment can have profound physiological, psychological, and potentially aging effects, which will certainly need to be addressed in a systematic fashion. The findings also shed some light on why traditional countermeasures have proven insufficient to prevent physiological decrements in space.

The last four decades of space exploration—from Projects Mercury and Vostok to the Space Shuttle and *Mir*— have defined multiple requirements for space medicine that must be met in order to ensure safe, long-duration missions:

1. Medical practitioners must be able to treat crew members for a wide range of illness, injury, or psychosocial matters and return the crew members to effective duty;
2. Medical practitioners must maximize the chance of mission completion and successful elective return, while minimizing the impact of a crew member's illness or injury to other crew members;

3. Medical practitioners and mission planners must provide for the stabilization and timely evacuation of a sick crewmember to a definitive care facility without jeopardizing the safety of the remaining crew; and
4. Mission planners and engineers must provide for timely consultation via telemedicine.

Criteria by which these requirements may be measured for effectiveness include an astronaut's ability to function as a productive member of the flight crew and perform assigned duties, the ability to maintain adequate orthostatic tolerance during de-orbit and landing, and the ability to execute rapid and unaided egress from the spacecraft.

In addition to the physiological changes, previous human space flight has defined occupational issues in space medicine. These issues include:

- selection of space flight personnel
- medical training
- life support
- extravehicular activity
- postflight rehabilitation and therapy
- radiation protection
- habitability of the spacecraft environment
- human factors considerations
- psychology and group dynamics

Current in-flight medical capabilities meet some of these requirements. On the Space Shuttle, for instance, a medical kit is flown on each flight, and at least one crewmember is trained to deliver basic medical care in the event of an emergency. Facilities on the ISS will include the Crew Health Care System (CHeCS), a multipurpose medical station for health maintenance, countermeasures, and environmental monitoring, and the use of the Crew Return Vehicle as an "ambulance" or "lifeboat" if needed.

Exploration-class missions beyond low-Earth orbit and into the remoteness of interplanetary space, however, will necessitate a unique set of requirements for health care systems. This equipment must be compact, lightweight, portable, user-friendly, autonomous, and minimally invasive. Space medicine practitioners have several areas in which to investigate potential health care solutions. Select applications of molecular biology and artifical gravity, for instance, may serve as tools for clinical practice in space, but have yet to be fully evaluated. Medical informatics applications, on the other hand, are already in use and are another valuable instrument for space-based health care.

Medical informatics is the integration of telecommunications, information, human-machine interfaces, and biologically-inspired technologies to enhance the delivery of health care to and in remote locations. The applications of medical informatics technology are widespread and not limited solely to health care, and they include: remote monitoring (of systems and environments); remote education and training; and observation, data collection, and operation of instruments from a remote location. Whether applied on Earth or during space flight, medical informatics technology will improve health care and quality of life.

Many of these technologies already exist. Today, medical informatics technology is used for telemedicine, telescience, telehealth, and teleducation. From this beginning, medical informatics designers are focusing on several trends that will further aid in the practice of space medicine on long-duration missions:

- **Haptic "Smart" Systems**—cybersurgery, microsurgical probes, and tissue engineering;
- **Miniaturized Technology**—x-ray, ultrasound, and MRI;
- **Virtual Reality**—improvement of surgical skills, testing of new techniques and immersive robotic surgery, preplanning for surgery;
- **Portable Equipment**—"smart" t-shirts and suits that relay information about the wearer to monitoring equipment, biochemical probes, innovative displays like the "heads-up" display that allow a maximum of monitoring with a minimum of space and intrusion; and
- **Biologically-Inspired Technologies**—artificial trunks, tentacles, and whiskers; adaptive automation, multipurpose tactile interfaces, and cognitive prostheses; artificial spider as drag-line silk; functionally-adaptive biomimetics; wireless biosensors.

The practice of medicine in spaceflight continues to evolve. The first four decades of human space flight have demonstrated the physiological changes experienced in microgravity and the occupational and clinical issues. In the coming years, new challenges requiring unique solutions are expected (increased flights, extended stays, and more varied crew populations) as the human presence in space becomes more complex. In the future, biomedical research will allow humans to safely and successfully complete long-duration exploratory missions, with the primary objectives of both settling the solar system and acquiring full cultural, social, and medical autonomy or simply exploring and returning to Earth.

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